Final report

Project Title:
Wireless Damage Monitoring of Laminated CFRP composites using Electrical Resistance Change

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Researcher:
Professor Akira Todoroki
Department of Mechanical Sciences and Engineering, Tokyo Institute of Technology
2-12-1-I-58, O-okayama Meguro-ku, Tokyo 152-8552, Japan
TEL/FAX: +81-3-5734-2809
E-mail: atodorok@ginza.mes.titech.ac.jp

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ABSTRACT
It is difficult to detect delamination of rotating composite components like helicopter and wind turbine blades while in-service with a wired system. In the present study, a wireless system using a tiny oscillation circuit for detecting delamination of carbon/epoxy composites is proposed. In this system, a tiny oscillation circuit is attached to the composite component. When delamination of the component occurs, electrical resistance changes, which causes a change in the oscillating frequency of the circuit. Since this system uses the composite structure itself as a sensor and the oscillating circuit is very small, it is applicable to rotating components. The electrical resistance change and oscillating frequency change due to delamination is experimentally measured using carbon/epoxy specimens. The effects of temperature changes are also measured. The wireless method is found to successfully detect embedded delamination, and to estimate the size of the delamination. The effect of temperature change is minimized by means of a temperature compensation circuit.

Keywords: A. Carbon fiber; A. Smart Materials; B. Electrical properties; C. Delamination; D. Nondestructive testing.

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1. Introduction

Composite laminates have high specific stiffness and strength, and so are widely used. However, they also have low delamination resistance, which allows delaminations to occur from slight out-of-plane impacts. For rotating composite components such as helicopter blades [1-6], rotor shafts [7-10] or wind turbine blades [11], the delamination of the composite laminates causes low reliability. Since a delamination crack in a laminated composite is usually invisible, it is very difficult to detect the delamination while the component is in service; thus their low reliability. To improve this low reliability of rotating composite components, a wireless delamination crack detection system for in service application is required. Systems that will monitor laminated composites by detect delamination cracks are desired as a practical approach to the health of laminated composites structures [12-21]. One of the approaches for detecting delamination cracks in service is to embed fiber-optic strain measuring sensors into laminated composite structures [12, 13]. This approach, however, may cause reductions in static and fatigue strengths, as shown by Seo and Lee [14]. Unfortunately fiber optic sensors and sensing systems are expensive and it is a difficult method to adapt as a wireless sensor.

Todoroki et al. [15, 16] have proposed an electro-resistance-change method [15-19], which does not require expensive instruments, to identify internal delamination cracks. Since the method adopts the composite laminate itself as the sensor for delamination detection, this method does not cause any reductions of static or fatigue strengths, and is applicable to existing structures. However, the resistance-change method has been limited to wired measurements. Problems have been encountered applying this method to the wireless system.

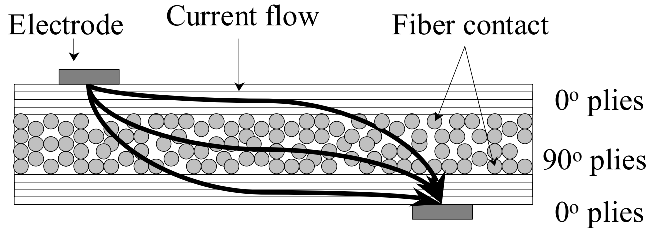
Although strain sensors using MEMS (Microelectromechanical system) [22] or SAS (surface-antenna-structure) [23] have been proposed as wireless sensor systems, a method for wireless detection of delamination has not been developed.

The present study proposes a method for wireless detection of delamination cracks using electro-resistance-change and the oscillating frequency changes of a tiny ceramic oscillating circuit. Since this method adopts the composite laminates itself as a sensor and the ceramic oscillating circuit is very small and lightweight, it is applicable to composite rotating components. It is also low cost. The electrical resistance and oscillating frequency changes due to delamination creation is experimentally measured using carbon/epoxy specimens. The effect of the environmental temperature change on these specimens is also experimentally investigated.

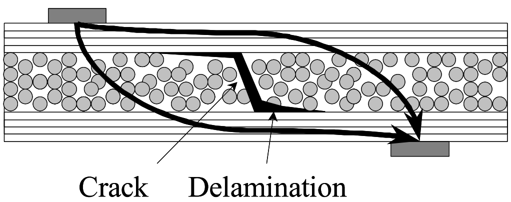
2. Monitoring system

Carbon fiber has high electric conductivity while the polymer matrix of a carbon fiber reinforced plastic (CFRP) is an insulating resistor. For ideal CFRP composites, the electric resistance in the fiber orientation is very small, and that in the transverse orientation is ideally infinity if we can imagine perfectly aligned straight carbon fibers. However, practical CFRP laminates have finite electrical resistance in every direction. Curved carbon fiber creates a large carbon-fiber network produced due to the fiber contacts in a ply; which brings about finite electric resistance in the transverse orientation. In the same way, the fiber-contact-network produces finite electrical resistance even in the thickness orientation in a ply. Electrical resistance in the transverse direction is much larger than that in the direction of the fiber orientation. If a delamination crack starts growing in the resin-rich interlaminate, the crack breaks the fiber-contact-network between the plies. The breakage of the contact network causes an increase in the electrical resistance of the carbon/epoxy-laminated composites, which enables delamination crack detection by measuring the electrical resistance change in a CFRP composite laminate.

Todoroki et al. [15, 16] proposed a set of aligned electrodes on one side of CFRP laminates to detect the delamination cracks from inside shell type structures. Although this setup of electrodes is useful when amplifiers can be used, the electrical resistance change due to delamination cracks is too small to detect wirelessly because the electrical current in the thickness direction is very small [24, 25]. In the present study, to increase the electrical current in the thickness direction, two electrodes are attached, one to each side of the composite laminate, as shown in Fig. 1. A delamination crack is then detected using the electrical resistance change between the two mounted electrodes. Since the structure of the CFRP composite itself performs as a sensor, there is no need to embed a sensor in the composite laminate, which prevents any reduction of static and fatigue strengths.



(a) Electrical network structures of the fiber in a CFRP laminate.



(b) The electrical network is broken with a delamination.

Fig. 1. Schema of a practical structure of a carbon/epoxy composite when an electrical current is applied.

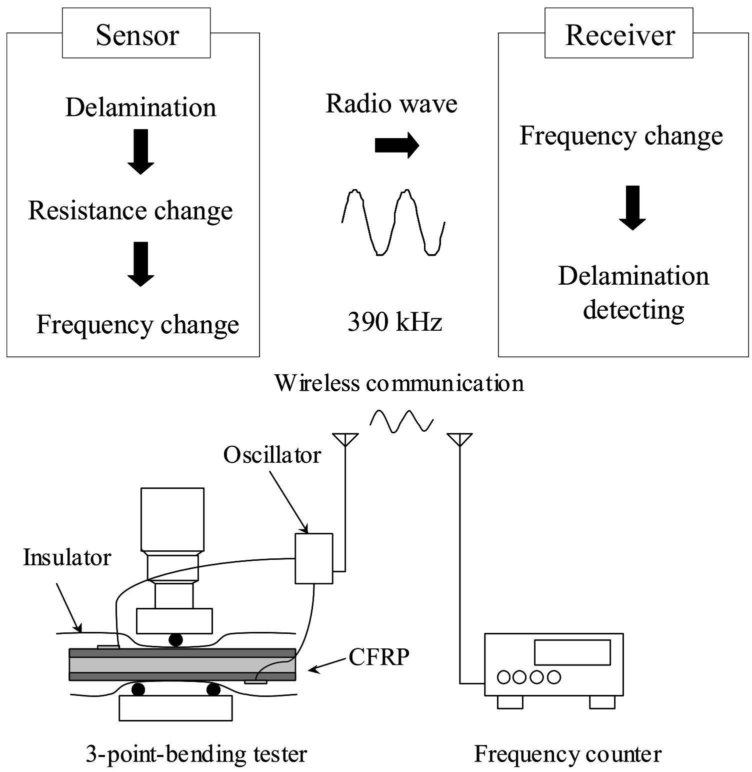


Fig. 2. Schematic representation of the wireless delamination-detecting system using electrical resistance and oscillating frequency change.

Fig. 2 shows a schematic image of the wireless delamination detection system. The system is composed of a sensor module that has a ceramic oscillator connected to the electrodes mounted on the composite surface, and a receiver composed of a receiving antenna and a frequency counter. The ceramic oscillator of the sensor module is used for wirelessly transmitting the electrical resistance change data as the oscillating frequency changes to the receiver; while the frequency counter is used for calculating the frequency of the emitted oscillating waves.

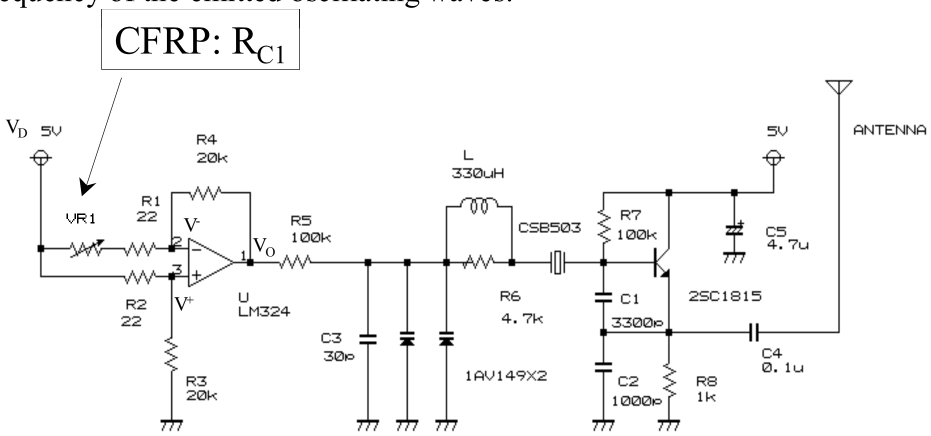


Fig. 3. Circuit diagram of the sensor circuit for wireless detection of delamination.

The sensor comprises mainly a differential amplifier (direct-current circuit) and an oscillating circuit (alternating-current circuit) as shown in Fig. 3. The set of electrodes mounted on the CFRP laminate is connected to the sensor circuit as VR_1 in front of the deferential amplifier, as shown in Fig. 3 where the electrical current I_1 which flows into VR_1, R_1 and R_4, and I_2 which flows into R_2 and R_3 are calculated as follows.

$$I_1 = \frac{V_D - V_O}{R_{C1} + R_1 + R_4} \qquad (1)$$

$$I_2 = \frac{V_D}{R_2 + R_3} \qquad (2)$$

where R_{C1} is the electrical resistance of CFRP laminate as a resistor VR_1, V_O is output voltage of the differential amplifier, and V_D is the voltage applied into the CFRP laminate, VR_1, as shown in Fig. 3.

The voltages at the inverting input terminal, V^-, and the noninverting input terminal, V^+, of the OP amplifier are obtained as follows.

$$V^- = V_D - I_1(R_{C1} + R_1) = \frac{V_D R_4 + V_O(R_{C1} + R_1)}{R_{C1} + R_1 + R_4} \qquad (3)$$

$$V^+ = I_2 R_2 = \frac{V_D R_2}{R_2 + R_3} \qquad (4)$$

The output voltages of a differential amplifier, V_{O1} and V_{O2} due to V^- and V^+, respectively, can be expressed as follows.

$$V_{O1} = -KV^- \qquad (5)$$

$$V_{O2} = KV^+ \qquad (6)$$

Where K is the gain of the amplifier. Since the output voltage V_O is the sum of V_{O1} and V_{O2}, the following equation is obtained from Eqs (3), (4), (5) and (6)

$$V_O = V_{O2} + V_{O2} = K\left\{\frac{V_D R_3}{R_2 + R_3} - \frac{V_D R_4 + V_O(R_{C1} + R_1)}{R_{C1} + R_1 + R_2}\right\} \qquad (7)$$

Since the K is regarded as infinity, ideally. The output voltage V_O is calculated as follows.

$$V_O = \frac{V_D}{R_2 + R_3} \cdot \frac{R_{C1}R_3 + R_1R_3 - R_2R_4}{R_{C1} + R_1} \qquad (8)$$

In the sensor circuit used here, R_1 is equal to R_2 (=24 Ω), and R_3 is equal to R_2 (=200 kΩ). The voltage applied to the CFRP laminate, V_D, is 5 V. The output voltage V_O is expressed as follows.

$$V_O = \frac{5R_4}{R_1 + R_4} \cdot \frac{R_{C1}}{R_{C1} + R_1} \qquad (9)$$

Since resistances R_1 and R_4 are constant, the output voltage V_0 increases with the increase of the resistance of the CFRP laminate, R_{C1}, due to the occurrence of the delamination.

The oscillating circuit used is a Colpitts type oscillator using a ceramic transducer. The oscillating frequency of this circuit decreases with increases of the electrical capacitance of the variable capacitance diode, 1AV149, as shown in Fig. 3. The electrical capacitance of the variable capacitance diode decreases with increases of the output voltage of the OP amplifier, V_O. Therefore, the oscillating frequency of the sensor circuit increases with increases of the electrical resistance of CFRP laminates: indicating the occurrence of delamination in the CFRP laminates.

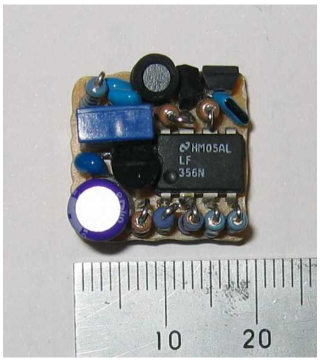


Fig. 4.The sensor circuit.

Since the sensor is mainly comprised of one transistor and one ceramic oscillator that generates more stable oscillating waves than a CR or LC oscillating circuit, it is possible to produce a small and light sensor. Moreover, the ceramic oscillating circuit needs no adjustment and it is low cost. The configuration of the sensor shown in Fig. 4 is 20 mm length, 15 mm width, 10 mm height and 4-gram weight. The tiny circuit enables the implementation of a sensor for existing structures without any difficult or complicated changes. Since transmitting the signal wirelessly from the sensor to the receiver is conducted by means of an oscillating frequency change as analog data, there is no delay of the signal for transmitting the electrical resistance data.

When n multiple channels are demanded, the required number of sensors is n, but only a single receiver is needed. To distinguish each output signal, each sensor has to use different initial tuning frequencies from each other: $f_1, f_2, \ldots, f_n$. The power spectrum P_k relating to sensor k has a peak at the initial tuning frequency f_k. The power spectrum P of the received signal with the external receiver is the sum of the power spectrum P_k of each sensor as follows.

$$P = \sum_{k=1}^{n} P_k(f) \qquad (10)$$

Since the power spectrum, P, has n peaks at the each initial tuning frequency, f_k, measurement of the frequency change of each peak enables us to obtain the electrical resistance changes of the multi-channels when each peak of the initial frequency has enough spacing.

3. Experimental procedures

3.1 Specimen configuration

The specimen is fabricated using PYROFIL #380: a unidirectional carbon/epoxy prepreg produced by Mitsubishi Rayon Co. Ltd. The stacking sequence of the laminates is $[0_2/90_2]_S$. An air vacuum method is used for curing process, the curing temperature is 130 ºC, the time 90 min, and the pressure 0.7 MPa. The configuration of the specimen is 50 mm length, 20 mm width, and 1.8 mm thickness, as shown in Fig. 5. The fiber volume fraction of the manufactured CFRP laminates is approximately 0.61. To measure the electrical resistance change from a delamination crack, two electrodes are mounted, one on each side of the specimen's surfaces. The electrodes are fabricated with silver paste after polishing the CFRP laminates with sand paper, and are covered with epoxy resin for protection.

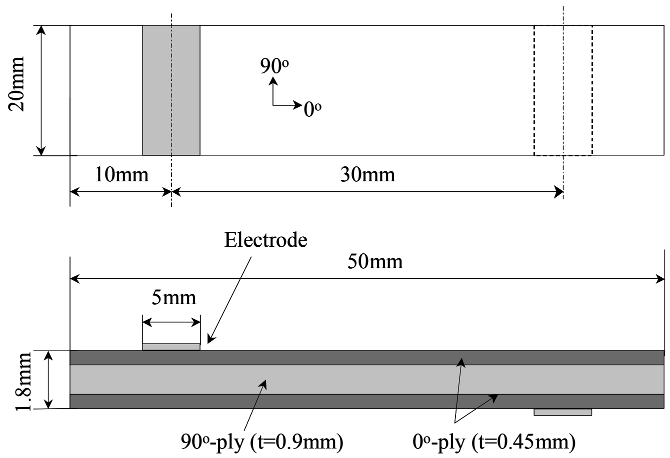


Fig. 5. Specimen configuration.

3.2 Electrical resistance change

To create an embedded delamination crack in the specimen, an interlamina shear test is performed as shown in Fig. 6. The span of the test is set to 10 mm, and the load is applied by tensile testing machine produced by Shimazu Co. Ltd. under the displacement-controlled condition of a crosshead speed of 0.1 mm/min.

First, the frequency response of electrical resistance and the phase angle of the impedance are measured using a LCR meter HiTESTER3522 produced by Hioki Co. Ltd. An interlamina shear test is performed on the CFRP specimen, and the electrical resistance measured. After the test, the configuration of the delamination crack is observed by an ultrasonic C-scan and a microscope.

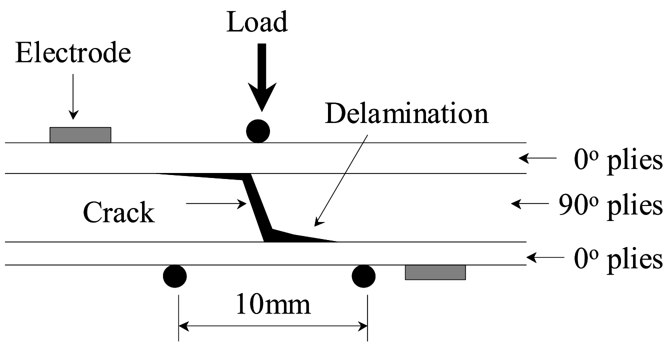


Fig. 6. Generation of a delamination crack by 3-point-bending test.

3.3 Oscillating frequency change

The oscillating frequency change of the sensor due to the creation of the delamination crack is measured by a frequency counter, a TR5822 produced by ADVANTEST Co. Ltd. The gate time of the frequency counter is set to 10 sec.

4. Results and discussion

4.1 Electrical resistance change

Fig. 7 shows the frequency response of the electrical resistance and the phase angle of the impedance of the CFRP laminates. The abscissa is the measuring frequency and the ordinate is electrical resistance and the phase angle of the impedance. The phase angle of the impedance is almost zero under a measuring frequency of 10 kHz and increases over this frequency. The increase of the phase angle means that the CFRP laminates is expressed as a parallel circuit of an inductor and a resistor over an alternating current of 10kHz. However, the sensor circuit applies direct current to the CFRP laminate as shown in Fig. 3, which enables a CFRP laminate to be considered as an electrical resistor because the phase angle of the impedance is zero under a measuring frequency of 10 kHz.

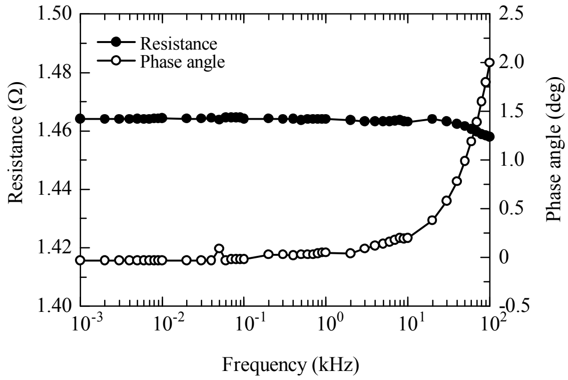


Fig. 7. Electrical resistance frequency response and the phase angle of the impedance of CFRP laminates.

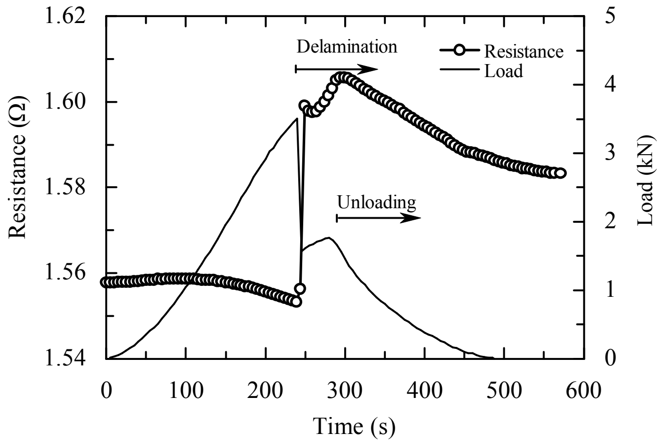
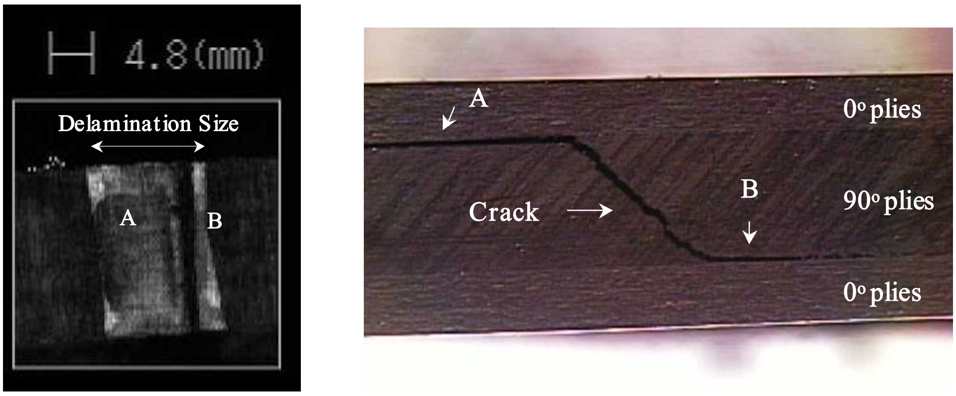


Fig. 8. Electrical resistance changes due to the generation of a delamination crack.

Fig. 8 shows the results of electrical resistance changes between two electrodes on CFRP laminates during interlamina shear tests. The abscissa is the time from applying the load to the specimen, and the ordinate is the electrical resistance and the applied load. As the load is applied, the electrical resistance decreases due to deformation. This change in the electrical resistance is reversible with unloading. However, the delamination at 250 sec interrupts the electrical current path, which causes a sharp resistance increase. After the unloading begins at 300 sec, the electrical resistance decreases again because part of the delamination crack closes again and the electrical contact is partially restored, which causes a decrease of the electrical resistance. Since broken connection is not fully restored after the unloading is completed, there is some residual electrical resistance as shown in Fig. 8.



(a) C-Scan image (b) Image of a cross section

Fig. 9. Delamination configuration of the CFRP laminates $[0_2/90_2]_S$.

Fig. 9(a) shows the configuration of the delamination cracks obtained by an ultrasonic C-scan. Fig. 9(b) shows the lateral face of the delamination viewed by a microscope. Parts A and B shown in Fig. 9(a), (b) indicate the delaminating area. From Fig. 9(b), it can be seen that the delamination is located at the upper interlamina between the 0° and 90° layers and at the lower interlamina between the 0° and 90° layers with a matrix crack in the middle 90° plies. The configuration of the delamination resembles the letter "Z"; thus, it is called a Z-type delamination crack, and is generally observed [16, 25].

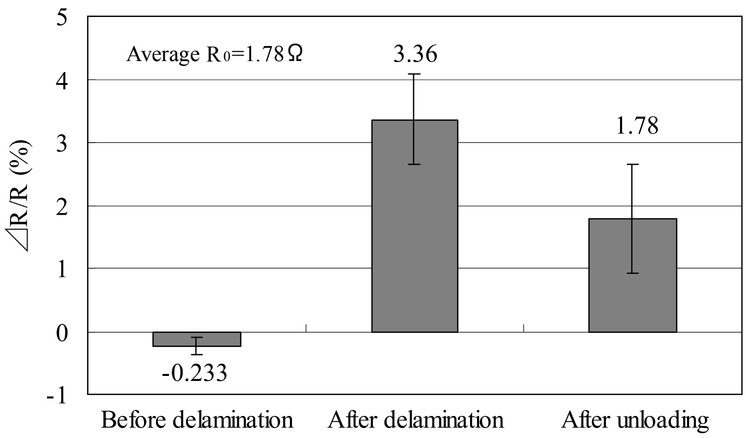


Fig. 10. Resistance changes with the generation of a delamination crack (average of 9 specimens) in four situations; initial electrical resistance, before delamination, after delamination and after unloading.

Fig. 10 shows the averages of four conditions for the specimens; the initial electrical resistance of the composite laminates, the electrical resistance just before the delamination, the electrical resistance just after the delamination, and the electrical resistance after unloading, obtained in nine specimens. The average of the initial electrical resistance is 1.78 Ω and the resistance change due to the creation of the delamination, $\Delta R/R$, is 3.37 %, which is large enough for an oscillation circuit to detect the delamination occurrence.

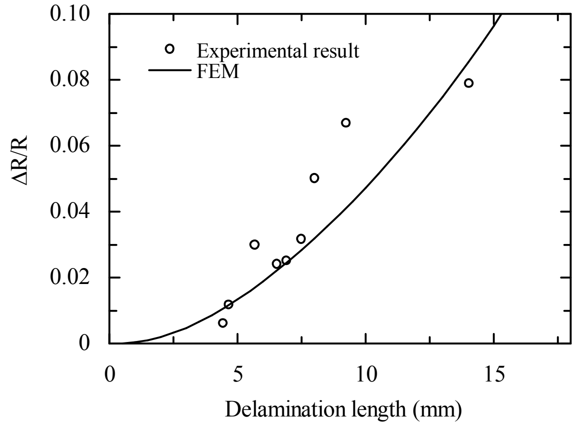


Fig.11. Relationship between the ratio of the electrical resistance change, $\Delta R/R$, and the size of the delamination.

Fig. 11 shows the relationship between the electrical resistance change and the size of the delamination as shown in Fig. 9. The abscissa is the delamination size and the ordinate is the electrical resistance change, $\Delta R/R$. The open circle symbols show the experimental results and the solid curve shows the results of numerical analyses, which are conducted using the FEM application program, ANSYS. The specimen is modeled with a two-dimensional and four-node plane element using the material type 55 of ANSYS. The size of the each element is 0.0625 mm in the thickness direction and 0.25 mm in the longitudinal direction. The number of the elements is about 3400, and there are about 3200 nodes. The delamination is modeled by means of doubly defined nodes where the delamination occurs and the doubly defined nodes on the delamination crack surfaces are released with each other to represent electric current insulation [26]. For simplicity, the microscopically heterogeneous CFRP is modeled as a uniform anisotropic material [24]. To obtain good agreement between the analysis and experimental results, the electrical conductivity of the CFRP laminates is determined by minimizing the sum of the square error of the electrical resistance change between the analysis results and the experiment results in all cases. In the analytical model, the ratio of the electrical conductivity between the 0° and 90° directions ,σ_{90}/σ_0, adopted here is 5.0×10^{-3}; and the ratio between the 0° and thickness directions, σ_t/σ_0, is 1.8×10^{-4}. As shown in Fig. 11, the electrical resistance change ratio, $\Delta R/R$, increases with an increase in the delamination size, which agrees with the FEM results. These results clearly indicate that the delamination can be detected by electrical resistance changes and that the electrical resistance change ratio enables the estimation of the size of the delamination.

4.2 Oscillating frequency change

Fig. 12 shows the results of the oscillating frequency changes due to electrical resistance changes in a CFRP laminate, which is used as a resistor in an oscillating circuit, as VR_1. The abscissa is the electrical resistance of the resistor element and the ordinate is the oscillating frequency generated from the sensor circuit. As shown in Fig. 12, there is a linear relationship between the electrical resistance, R, and oscillating frequency, f_0, which is obtained as follows.

$$f_0 = 0.0922R + 390.589 \qquad (11)$$

Fig. 13 shows the power spectrum obtained by means of the FFT of the transmitting wave of the sensor output using the CFRP laminate as an electrical resistor, VR_1 as shown in Fig. 3. The abscissa is the frequency and the ordinate is the power spectrum, which has a sharp peak at 390 kHz. This indicates that the sensor clearly generates the oscillating waves, even if the CFRP laminate is used as the electrical resistor in the sensor circuit.

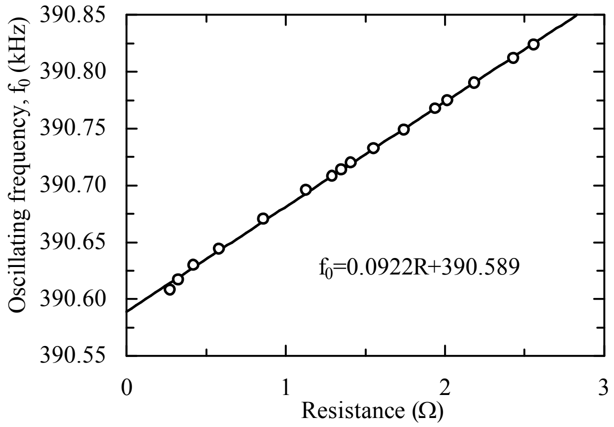


Fig. 12. Relationship between oscillating frequency and electrical resistance.

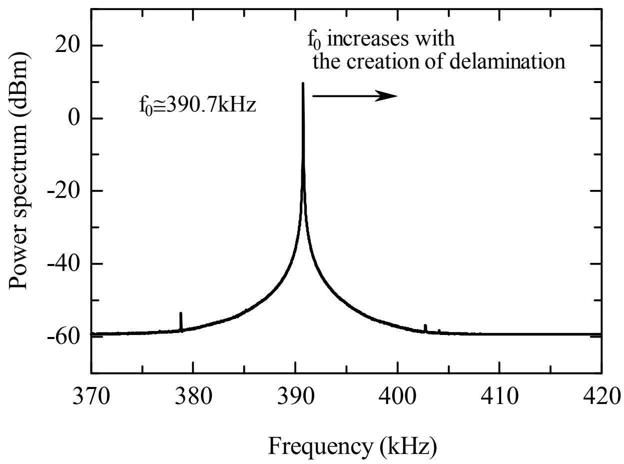


Fig. 13. The power spectrum of the oscillation frequency using a CFRP laminate as an electrical resistor of the sensor.

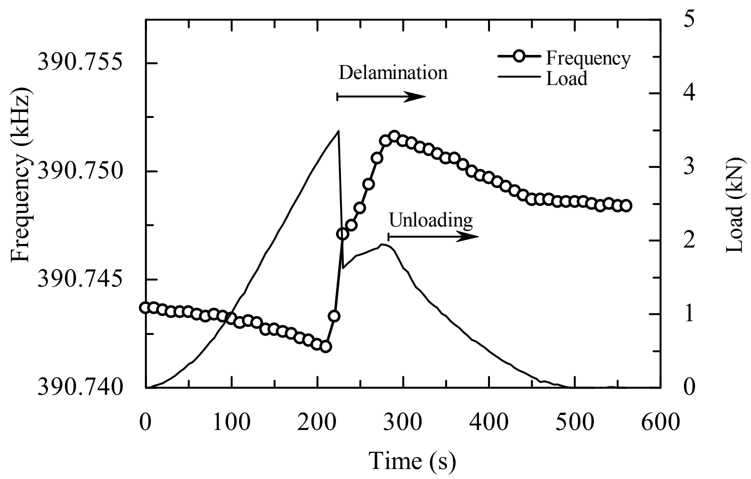


Fig. 14. Oscillating frequency changes with the generation of a delamination crack.

Fig. 14 shows the results of oscillating frequency changes measured wirelessly during a three-point-bending test. The oscillating frequency of the sensor decreases with increases of the applied load, and increases sharply when the delamination occurs. Although the oscillating frequency decreases with unloading, there is residual resistance even after the unloading is completed, which agrees with the results shown in Fig. 8.

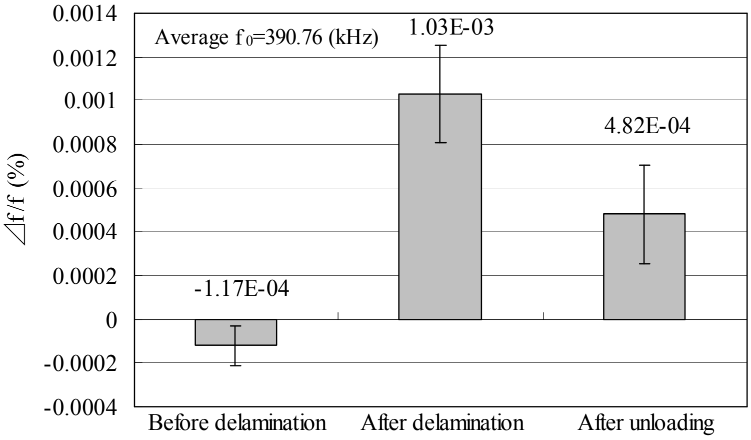


Fig. 15. Frequency changes with the generation of a delamination crack (average of 12 specimens) in four situations; initial electrical resistance, before delamination, after delamination and after unloading.

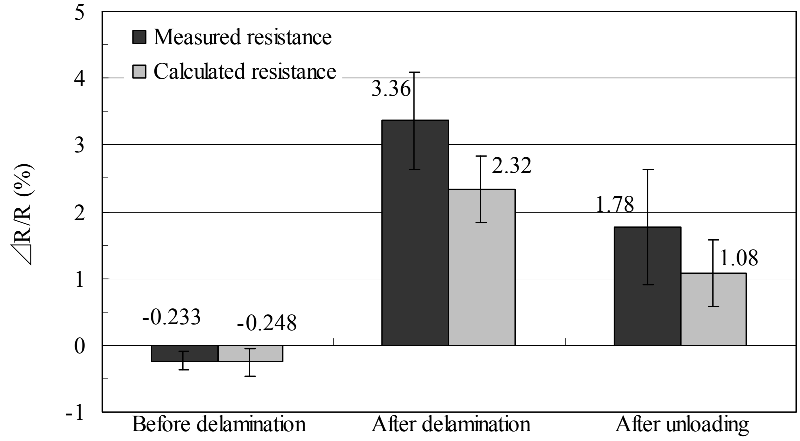


Fig. 16. Relationship between the measured electrical resistance and the converted electrical resistance from the oscillating frequency.

Fig. 15 shows the averages of four cases; the initial oscillating frequency of the sensor, the oscillating frequency just before the delamination, just after the delamination and after unloading, as obtained with 12 specimens. Fig. 16 shows the fraction of the electrical resistance, $\Delta R/R$, calculated from the oscillating frequency results shown in Fig. 12 using Eq. (11) compared with the measured electrical resistance change shown in Fig. 10. Although the characteristics of the calculated electrical resistance changes from the oscillating frequency correspond with the measured electrical resistance changes, the calculated electrical resistances have some differences compared to the measured electrical resistances. This difference is caused because the measurements of the resistance changes and the oscillating frequencies were performed at different times, which caused experimental errors and changes of the delamination crack surface contact. Although the fraction of the oscillating frequency change, $\Delta f/f$, is 2.32 %, smaller than that of the electrical resistance change of 3.36 %, the frequency change is large enough compared to the electrical resistance change of –0.248 % due to the deformation of the CFRP laminate.

Fig. 17 shows the relationship between the ratio of the oscillating frequency change and the size of the delamination area. The curved line shows the oscillating frequency change predicted by FEM analysis and Eq. (11). The oscillating frequency increases with increases of the delamination size, which agrees with the experimental results. Figs. 15, 16 and 17 show that by using the electrical resistance change due to the creation of the delamination and the sensor with the ceramic oscillator enables the wireless detection of the delamination and an estimation of the size of delamination.

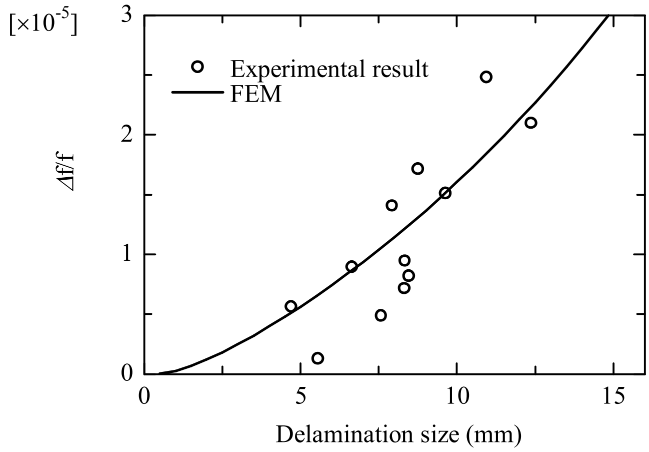


Fig. 17. Relationship between the frequency change ratio, $\Delta f/f$, and the delamination size.

4.3 Temperature compensation

In practical application, the effect of environmental temperature is not negligible. The effect of environmental temperature change on the oscillating frequency is examined using an electrical furnace, KOSMOS produced by Isuzu Co. Ltd., and a refrigerator. First, the electrical resistance of a CFRP laminate is measured with the changes of environmental temperature from –20 ºC to 80 ºC. Fig. 18 shows the results of the ratio of the electrical resistance change due to temperature change. The electrical resistance at a room temperature of 25 ºC is taken as the initial value. The abscissa is the environmental temperature measured by a thermo couple, and the ordinate is the ratio of the electrical resistance change, $\Delta R/R$. The electrical resistance of the CFRP laminate decreases as the environmental temperature rises, and is generally expressed as the temperature coefficient α defined as follows.

$$\alpha = \frac{R_{T2} - R_{T1}}{R_{T1}T_2 - R_{T2}T_1} \qquad (12)$$

where R_{T1} is the electrical resistance at temperature T_1, and R_{T2} is that at T_2. Although the temperature coefficient, α, of metals is generally a positive value, that of carbon is negative. The temperature coefficient of CFRP laminates is –54300 ppm/ºC, which indicates that a temperature change of about 30 ºC matches the change of electrical resistance due to the creation of delamination cracks.

Fig. 19 shows the results of oscillating frequency changes of the sensor output using CFRP laminates as an electrical resistor, VR_1. The abscissa is the measured temperature and the ordinate is the ratio of oscillating frequency change, $\Delta f/f$ (open circle), which decreases with the temperature rise and corresponds to the converted oscillating frequency change (solid circle) from the electrical resistance change shown in Fig. 18 and Eq. (11). These results indicate that the decrease of the oscillating frequency due to a temperature rise is mainly caused by the electrical resistance change of a CFRP laminate.

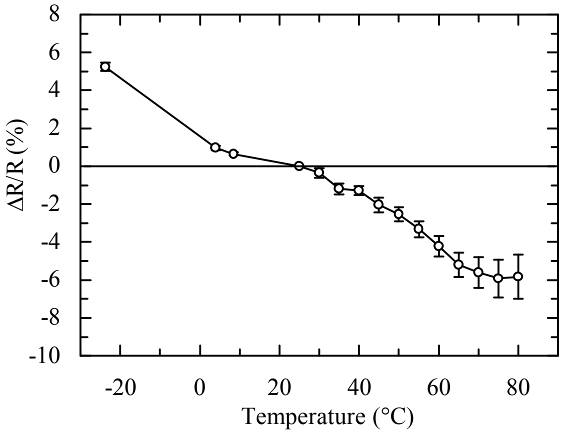


Fig. 18. Electrical resistance change measured with changes in the environmental temperature.

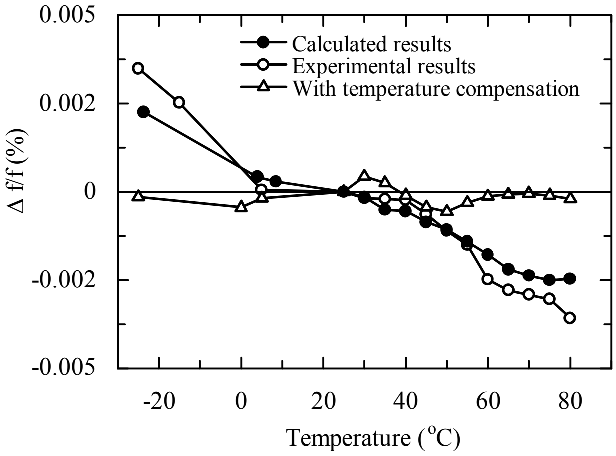


Fig. 19. Oscillating frequency changes of a circuit with and without temperature compensation.

To compensate for the change of the oscillating frequency due to the temperature change, another CFRP laminates whose configuration and electrical resistance, R_{C2}, is the same as the original one, as shown in Fig. 5, is connected in front of the differential amplifier as the electrical resistor, VR_2, as shown in Fig. 20, and the output voltage of the differential amplifier V_O is expressed as follows.

$$V_O = \frac{5R_4}{(R_{C1} + R_1)(R_{C2} + R_1 + R_4)}(R_{C1} - R_{C2}) \qquad (13)$$

Since the output voltage of the differential amplifier, V_O, is zero when the two electrical resistances are equal (R_{C1}=R_{C2}), the same electrical resistance changes of the two CFRP laminates due to the temperature change enable temperature compensation for the sensor circuit. Since only VR_1 increases and VR_2 is constant when delamination occurs, the oscillating frequency increases and the delamination can be detected.

Open triangles in Fig. 19 show the oscillating frequency changes of a temperature compensated circuit that has two CFRP laminates, as VR_1 and VR_2, due to the change of environmental temperature. The change of the oscillating frequency is within ± 0.001 % and does not affect the detection of the delamination; thanks to the temperature compensating system proposed here. On the basis of these results, we conclude that the proposed sensor system is feasible even in an environment with temperature-changes.

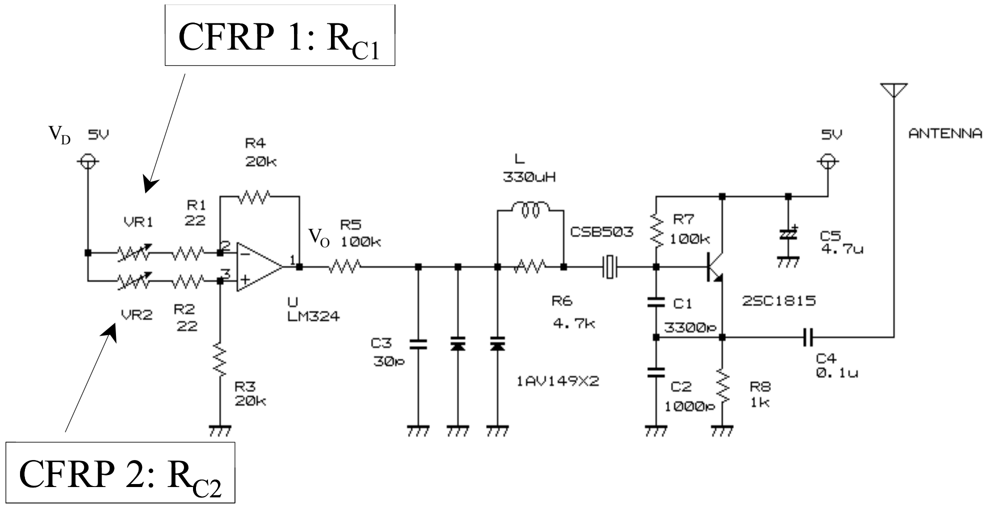


Fig. 20. Temperature compensated sensor circuit for wireless detection of delamination.

5. Conclusions

The present study demonstrates that the occurrence of delamination cracks can be monitored wirelessly with an oscillating circuit using the electrical resistance change method. The system developed here was applied to CFRP laminates $[0_2/90_2]_S$, and the following results obtained:

(1) A wireless crack detection system is proposed using electrical resistance changes and a ceramic oscillating circuit. Crack creation testing is performed with CFRP laminates, and delamination cracks detected wirelessly.

(2) The delamination size is measured wirelessly using oscillating frequency changes due to the crack occurrences in CFRP laminates.

(3) Although the resistance between electrodes on the CFRP surface is sensitive to environmental temperature changes, the effect is made negligible by means of our proposed temperature compensated system utilizing two CFRP laminates.

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